Vibration Monitoring to Diagnose Incipient Seizure of Crosshead Bearings*

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A technique to monitor abnormal vibration of crosshead bearings in large two-stroke diesel engines has been developed using a dynamically loaded bearing seizure test rig. The test rig is able to simulate the load pattern and oscillatory motion of the actual crosshead bearing. Normal vibration spikes occur around crank angles of -90deg and +90deg where the oscillating speed is zero. When the lubrication condition deteriorates, an abnormal vibration spike caused by severe metal-to-metal contact is frequently generated at a crank angle of +90deg where the oil film thickness is a minimum. If careful measures against seizure are carried out immediately after detecting abnormal vibration, the bearing surface would be able to recover, thereby avoiding severe metal-to-metal contact damage. Thus the early detection of abnormal vibration can be effective in preventing seizure of the bearings.

1. Introduction

The crosshead bearing in large two-stroke diesel engines operates under severe lubrication conditions, because it oscillates within a small angle at a low speed and is subject to a high specific load. The crosshead bearing has several axial oil-grooves on the loaded surface to promote oil film replenishment during bearing oscillation. Because the development of a thick oil film by hydrodynamic action is impaired by these oil-grooves, the bearing is more prone to damage by tribological failure. The continuing trend towards more compact engines with increased output raises the bearing specific load, leading to more severe operating conditions. Therefore, it is necessary to find a means to detect incipient seizure and prevent it [1] - [5].

A technique to monitor vibration using an accelerometer has already been adopted to detect the tribological degradation on many surfaces such as rolling bearings and gears [6]. For crosshead bearings, however, there are very few reports on monitoring techniques to detect the early stages of severe metal-to-metal contact prior to complete seizure. If careful measures against seizure could be carried out immediately after detecting incipient abnormal vibration, the surface damage would be reduced. Detection of abnormal vibration could therefore be an effective means of preventing seizure, and thereby improving the reliability of crosshead bearings.

2. Test Method

Figure 1 shows a schematic diagram of the test apparatus. The journal ① was oscillated through a small angle (2ф0=55 deg). The bearing ② was subjected to a cyclically fluctuating load applied vertically by an oil pressure ram ⑤. The lubricating oil was supplied to the bearing at a temperature of 60°C and a flow rate of 30 cm³/s by an oil feed pump ⑩. Figure 2 shows typical changes in the specific load Pw and the angular velocity ω during one crank revolution. Although the bearing and the load direction are fixed and the journal are oscillated in the apparatus, the test...
conditions of load pattern and relative oscillation are equivalent to those for crosshead bearings in actual engines.

Figure 3 shows the major dimensions of the bearing used in the tests. The bearing had four axial oil-grooves at a pitch angle of 40°. Figure 4 shows the detail of the oil-groove geometry. The lining material was white metal without overlay. The journal was manufactured from unhardened S55C carbon steel, and its sliding surface was finished to a centre line average height of 0.12 µm. The lubricating oil was SAE10W additive-free engine oil. Bearing seizure was instigated by either stopping the oil supply or gradually raising the specific load.

The vibration in the direction of oscillation was measured using a piezoelectric accelerometer attached to the side of the bearing housing as shown in Figure 5. The temperature was measured at the centre of the bearing using a thermocouple placed at a depth of 0.5 mm below the bearing surface. Three optical fibers were placed as shown in Figure 3. They will be discussed more fully later.

The electrical resistance of the oil film between the bearing and the journal was measured to evaluate the extent of oil film formation [4]. Figure 6 shows the electrical circuit. A voltage of 273 mV was applied to the bearing, which was electrically insulated from the bearing housing, while the journal was earthed. The output voltage $E$ was obtained from equation (1).

$$E = \frac{R \cdot R_1 \cdot E_0}{R_1 + R_2 + R_1 \cdot R_2}$$

Figure 7 shows that the output voltage $E$ varies between 0 and 273 mV depending on the electrical resistance of the oil film $R$. 

\[ E = \frac{R \cdot R_1 \cdot E_0}{R_1 + R_2 + R_1 \cdot R_2} \]
When the oil film is thick enough to prevent metal-to-metal contact, the electrical resistance of the oil film is infinite. This results in an output voltage of 273 mV. As the oil film thickness reduces, metal-to-metal contact increases and the electrical resistance of the oil film decreases, thereby causing the output voltage to drop to 0 mV. Figure 8 shows a typical variation in the output voltage $E$ during one crank cycle. The oil film formation ratio $F$ over one cycle was estimated from equation (2).

$$ F = \int_{-\theta_c}^{0} \frac{E_i - E_o}{E_{i0} - E_o} \, d\theta_c $$

(2)

The oil film thickness was measured using a laser induced fluorescence (LIF) method as shown in Figure 9. A dye added to the oil was made to fluoresce by illuminating the oil film from a laser diode emitting violet light with a wavelength of 405 nm, through an optical fiber. The emitted fluorescent signal was filtered at 530 nm and captured with a photon multiplier tube. The intensity of fluorescence increased in proportion to the oil film thickness. Three optical fibers were placed at the bearing centre, -10 deg and +10 deg in circumferential direction from its centre as shown in Figure 3. The attitude angle $\phi$, the eccentricity $e$ and the minimum oil film thickness $h_{min}$, as shown in Figure 10, were calculated using the oil film thickness $h_1$, $h_2$, $h_3$ and the radial clearance $c$ from the following equations.

$$ h = c + e \cos \theta $$

(3)

$$ \phi = \tan^{-1} \left( \frac{h_1 - h_3}{2(c - h_2) \sin 10^\circ} \right) $$

(4)

$$ e = \frac{c - h_2}{\cos \phi} $$

(5)

$$ h_{min} = c - e $$

(6)

3. Test Results and Considerations

3.1 Abnormal Vibration in Seizure Test with the Oil Supply Stopped Off

Seizure was instigated by stopped off the oil supply to allow the effects of impaired lubrication to be studied. Before stopping the oil supply, running-in was carried out under constant conditions of $N=300\text{cpm}$, $2\nu=55\text{deg}$, $P_{smax}=18\text{MPa}$. The clearance ratio $c/r$ was set to 0.0001. Figure 11 shows the typical changes in the vibration acceleration $V$ and the output voltage $E$ during one crank cycle. Under normal lubrication conditions...
established before stopping the oil supply, as shown in Figure 11 (a), normal vibration spikes occurred around crank angles of -90 deg and +90 deg where the oscillation speed was zero. This is probably because some stick-slip phenomenon happened as the journal reversed direction, creating a friction spike [7]. Figure 11 (a) also shows the output voltage $E$ during one crank cycle. When the oil film was thick enough to prevent metal-to-metal contact, i.e. around bottom dead centre under conditions of low specific load and high oscillating speed, the electrical resistance of the oil film was high, resulting in an output voltage of 273 mV. Conversely, because the oil film thickness degenerated into boundary lubrication from around top dead centre under a heavily loaded condition to 90 deg crank angle under a very low speed condition, the electrical resistance of the oil film decreased, resulting in an output voltage of 0 mV. The oil film formation ratio $F$ was 62%.

Figure 11 (b) shows the vibration acceleration $V$ and the output voltage $E$ obtained 570 seconds after the oil supply was stopped. Because the lubrication condition continued to degenerate after stopping the oil supply, the oil film became thinner, resulting in an output voltage of 0 mV throughout the crank cycle and implying continuous boundary lubrication conditions. An increase in the vibration spike occurred at a crank angle of approximately +90 deg. However, the vibration amplitude signature was unchanged at other crank angles. Figure 11 (c) shows the vibration acceleration $V$ and the output voltage $E$ obtained 790 seconds after cutting off the oil immediately before seizure occurred. The vibration spike increased significantly at a crank angle of approximately +90 deg. However, the vibration amplitude at all other crank angles remained substantially the same.

Figure 12 shows the cyclic variations in the oil film thickness $h_1$, $h_2$ and $h_3$, the minimum oil film thickness $h_{\text{min}}$ and the attitude angle $\phi$, all derived from the LIF measurements. The attitude angle $\phi$ varied within the small range from -11 deg to 10 deg. The oil film thickness reached its lowest value not at 0 deg crank angle where the specific load was maximum, but just after +90 deg crank angle where the oscillation speed was zero. The oil film thickness became a maximum at a crank angle of approximately -100 deg. The oil film thickness at +90 deg crank angle was significantly lower than at -90 deg crank angle. This is why the abnormally increased vibration spike was observed at this position in the cycle when lubrication was severely impaired. Namely, metal-to-metal contact was frequently generated at a crank angle of approximately +90 deg where the oil film thickness was at its lowest value.

Figure 13 shows the vibration acceleration $V$ monitored...
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continuously throughout 10 crank cycles. Under normal lubrication condition established before stopping the oil supply, the vibration signal was very similar throughout all 10 cycles. 570 seconds after the oil supply was stopped off, six of the ten cycles displayed an abnormally increased vibration spike while the amplitude of the vibration spike was unchanged in the other four cycles. This demonstrated that oil film rupture and subsequent recovery were repeated during initial severe metal-to-metal contacts. However, because oil film rupture was more extensive after 790 seconds, complete oil film recovery could not occur, thereby creating the abnormally increased vibration spikes in all 10 cycles.

Figure 14 shows how the abnormal vibration occurrence ratio, shown as X in Figures 11 and 13, was defined. The vibration spikes at +90 deg crank angle produced under the normal lubricating conditions established before stopping the oil supply was set to V₀. The vibration spike increased to Vₘ when the oil supply was stopped off to impair lubrication. The threshold level of vibration amplitude Vₘₐₓ was set at 1.2 V₀. When the vibration spike Vₘ exceeding the threshold level Vₘₐₓ, the vibration spike was defined as abnormal. The occurrence ratio X was defined as the number of times the abnormal vibration occurred, expressed as a percentage of the total number of cycles.

When the abnormally increased vibration spike caused by severe metal-to-metal contact is generated frequently, there is a high possibility of seizure. Abnormal vibration occurrence ratios higher than 50 % indicate that the rate of oil film rupture is more significant than the rate of oil film recovery. Therefore, the acceptability threshold of the abnormal vibration occurrence ratio X was set at 50 %, as shown in the following section.

3.2 Abnormal Vibration in Seizure Test with Increasing Specific Load

One further seizure test was carried out, in which the lubrication condition was impaired by gradually raising the specific load. Before the test, running-in was performed under constant conditions of N=300 cpm, 2ϕ=55 deg, Pₖₘₐₓ=20 MPa. The maximum specific load Pₖₘₐₓ was then periodically increased at a rate of 0.2 MPa / 30 seconds until seizure occurred. The clearance ratio c/r was set to 0.0005.

Severity of the effects of impaired lubrication was evaluated by means of the abnormal vibration occurrence ratio X. The vibration spike obtained under the normal condition at a moderate specific load of 20 MPa was determined as V₀. The threshold level Vₘₐₓ was set to 1.2 V₀. When the vibration spike exceeded the value of Vₘₐₓ, it was defined as abnormal. The ratio of abnormal vibration spikes to total cycles, the abnormal vibration occurrence ratio, was determined as X at each level of specific load.

Figure 15 shows the changes in surface temperature T, oil film formation ratio F, root mean square (RMS) value of vibration acceleration Vₐₘₐₓ and abnormal vibration occurrence ratio X when...
the maximum specific load $P_{\text{max}}$ was increased. The values of the surface temperature $T$ and $V_{\text{rms}}$ increased rapidly at the specific load of $P_{\text{max}} = 24$ MPa immediately before seizure occurred. The oil film formation ratio $F$ dropped to 0 mV at a significantly lower specific load of $P_{\text{max}} = 21.8$ MPa. Therefore, these lubrication parameters are not adequate to diagnose the onset of seizure.

The abnormal vibration rapidly increased in frequency at the specific load of $P_{\text{max}} = 23.2$ MPa, thereby causing the abnormal vibration occurrence ratio $X$ to reach 50%. This demonstrates the beginning of severe metal-to-metal contacts leading to seizure.

3.3 Measures against Seizure after Detecting Abnormal Vibration

The test operational conditions were modified to take measures against seizure immediately after the abnormal vibration occurrence ratio $X$ exceeded 50%. Namely, the rate of increase of specific load was reduced from 0.2 MPa/30 seconds to 0.2 MPa/240 seconds, as shown in Figure 16. Figure 17 shows the changes in surface temperature $T$, oil film formation ratio $F$, root mean square value of vibration acceleration $V_{\text{rms}}$ and abnormal vibration occurrence ratio $X$, after the operation was modified in this way. The abnormal vibration occurrence ratio reached 50% at a specific load of $P_{\text{max}} = 22.2$ MPa, at which point the operation was modified for measures against seizure.

Because measures against seizure were carried out immediately after detecting the abnormal vibration, the bearing surface conformed to the journal and self-healed, re-establishing sufficient oil film thickness to avoid severe metal-to-metal damage. As a result, seizure no longer occurred when the specific load of $P_{\text{max}} = 24.2$ MPa was reached, at which seizure previously occurred without taking such measures. The monitoring of abnormal vibration can be an effective means to detect incipient lubrication degradation, and thereby prevent seizure of the crosshead bearings.

![Figure 15 Changes in values of $F$, $T$, $V_{\text{rms}}$ and $X$ by raising maximum specific load](image1)

![Figure 16 Modified operation after detecting abnormal vibration](image2)

![Figure 17 Improved load carrying capacity by modified operation after detecting abnormal vibration](image3)
4. Conclusions

From experiments conducted to detect the onset of abnormal vibration and subsequently prevent seizure of the crosshead bearing, the following conclusions were obtained:

(1) During the engine cycle, vibration spikes occur around crank angles of -90 deg and +90 deg where the bearing oscillating speed is zero. When lubrication is impaired, an abnormal vibration spike is generated at a crank angle of approximately +90 deg where the oil film thickness is a minimum. The frequency of this spike generation increases with the degree of impairment.

(2) It is impossible to detect the very beginning of the severe metal-to-metal contacts based on a bearing surface temperature measurement or the RMS value of vibration measurement. It is also difficult to predict the likelihood of seizure based on a sudden decrease in the oil film electrical resistance.

(3) Bearing seizure can be avoided by limiting the abnormal vibration occurrence ratio to 50%.

(4) If careful measures against seizure are carried out immediately after detecting abnormal vibration, the bearing surface is conformed, thereby avoiding severe metal-to-metal contact damage.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$V_{rm}$</td>
<td>Root mean square value of vibration acceleration</td>
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<tr>
<td>$W$</td>
<td>Bearing load</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Circumferential angular coordinate</td>
</tr>
<tr>
<td>$\theta_c$</td>
<td>Crank angle</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Attitude angle</td>
</tr>
<tr>
<td>$2\nu$</td>
<td>Bearing oscillation angle</td>
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<tr>
<td>$\omega$</td>
<td>Bearing angular velocity</td>
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